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THE USE OF THE CRITICAL THICKNESS CONCEPT IN DESIGN

TECHNICAL REPORT

by

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Material evaluation
Rocket motor materials

THE USE OF THE CRITICAL THICKNESS CONCEPT IN DESIGN

Technical Report AMRA TR 64-51

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ABSTRACT

A brief review of the "critical thickness" concept is presented. Three actual examples of solid rocket motor case designs are then discussed. In the first example, fracture toughness and/or "critical thickness" were not taken into account, but the case proved adequate. In the second example, a design based on the success of the first case proved inadequate because of an increase in section thickness. In the third example, the "critical thickness" was properly considered and no brittle failure problem arose. After the discussion of these histories, a simplified technique for obtaining the critical thickness data required for adequate design is presented.

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INTRODUCTION

During the past 10 years many papers dealing with various aspects of notch sensitivity, brittle fracture, and fracture toughness have appeared in the technical literature. Collectively, these papers do not constitute a quantitative basis for design against brittle fracture.[1,2,3] However, they do provide a qualitative design basis which can be used by designers to insure relative freedom from brittle service failures. Unfortunately, there are a good many factors which either individually or collectively affect the notch sensitivity of structural materials. Important factors include chemistry, melting practice, solidification practice, deformation processing, heat treatment, service environment, applied stress field, strain rate, etc. In some instances, relatively small changes in any one of these factors can cause a great change in the notch sensitivity of a structural alloy. For example, a change of only a few degrees in the heat treatment of precipitation-hardening stainless steels can result in severe embrittlement;[4] a test-temperature drop of a few degrees can result in a large increase in notch sensitivity in many lean-alloy low-carbon steels.[5] The literature contains references to many service failures of components where notch sensitivity was high because of inadequate control of any one of these important factors. Failures have also been noted where component geometry was inadequate, but these failures can usually be attributed to inaccurate calculation of the applied stress field. However, in thin-walled pressure vessels, failures due to component geometry have been shown to occur because notch sensitivity varied with section thickness independently of all other variables.[5,6,7] This report discusses a thin-walled design in which, in one case, the effect of section thickness on fracture toughness was the determining factor for insuring a satisfactory design. The application of existing semiquantitative fracture mechanics concepts to this design not only prevented design deficiencies but also indicated that the implicit assumption of "flawless" materials in more conventional design methods should be questioned in applications of very high-strength materials.

Design Concepts

Given the problem of brittle failure in high-strength steel materials, and realizing that small flaws or cracks in the material will act as initiation sites for crack growth leading to brittle failure, the designer has two choices; he can design on the basis of being able to detect <u>all</u> flaws, thereby producing a flawless material; or he can design on the basis of being able to accept small flaws or cracks, provided his material has adequate toughness to resist crack propagation. The first of these approaches, the "no flaw" concept, implies that solutions can be found for several very difficult practical problems: (1) production of defect-free sheet materials; (2) fabrication by welding and/or other joining techniques without the introduction of defects; (3) nondestructive testing with 100 percent certainty of locating small flaws; and (4) the elimination of defects which evolve by time-dependent processes (such as corrosion) subsequent to manufacture. The first of these problems might be eliminated by

use of the most advanced melting techniques (i.e., consumable electrode vacuum melting) together with solidification and deformation processes of the most advanced types. However, in the current state-of-the-art, the remaining three problems are formidable, to say the least. Welds of high integrity can be produced in the laboratory, but the state-of-the-art in production falls considerably short of that in the laboratory. In non-destructive testing, the present state-of-the-art is even farther below the desired level than it is in welding. Also, when the detection of small flaws is required, some arbitrary value must be established for "how small is small." The solution of the fourth problem is also unlikely within the forseeable future. Because of these problems, it is obvious that the "no flaw" design philosophy, while sound in theory, is unsound in practice. Therefore, the second design concept, which is more realistic, must be used. Some flaws which are assumed to be present in the material (either as cracks or regions of compositional inhomogeneities[8]), can be tolerated, but the material with the greatest resistance to crack growth at the lowest required temperature (and also with the necessary yield strength to satisfy the design requirements), must be used in order to inhibit brittle fracture.

Effective use of this second design concept requires the employment of the analytic tools of fracture mechanics by means of which the parameters of yield strength, applied stress, length of pre-existing materials flaws (cracks), and fracture toughness of the material may be related to one another. Fracture mechanics is an outgrowth of Griffith's[9] brittle failure theory as modified by Irwin[10,11] to take into account the plastically deformed zone which exists just ahead of the crack front in a metal. Fracture-toughness parameters which are used in fracture mechanics are: (1) K_c, or the critical stress-intensity factor,[12] and (2) G_c, or the critical energy release rate.* Each of these parameters is measured at the point in growth history where the crack becomes self-propagating due to the stored elastic energy. K_c has units of psi $\sqrt{\text{inch}}$ and G_c has units of inch-pounds per square inch.

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*Under plane-stress conditions, K_c for edge- or center-notched tensile specimens is calculated from the following expression:

$$K_c^2 = \sigma^2 W \tan \left(\frac{\pi a}{w} + f\right) \qquad (1)$$

where

K_c = measure of fracture toughness at point of crack growth instability

σ = gross section stress at onset of fast fracture

W = specimen width

a_c = 1/2 the crack length at the point of instability

f = a correction factor which depends on whether an edge- or center-notched specimen is used (see Reference 12).

$$G_c = K_c^2/E \qquad (2)$$

where

E = Young's modulus.

As a result of combining the analytic discipline of fracture mechanics with the art of fractographic studies,[13] the concept of "critical thickness" as a means to maximize fracture toughness in steels has arisen. At this juncture, it would be well to review the concept of critical thickness with regard to the fracture toughness of thin sheet materials.

Critical Thickness Concept

It is known that as the thickness of steel is increased from very thin sheets, the fracture toughness increases until a certain thickness is reached - the critical thickness - at which point the fracture toughness begins to fall with further increases in thickness.[1,5,6,7] Eventually, the value of the fracture toughness becomes constant with regard to section thickness. This constant value of fracture toughness is the plane-strain fracture toughness; whereas, the fracture toughness on the rising portion of the curve is the plane-stress fracture toughness, and the fracture toughness on the falling portion of the curve is a combination of plane-stress and strain-fracture toughness. This is illustrated in Figure 1. For thicknesses at and below the critical thickness the fracture occurs by a 100 percent shear mode; and for thicknesses greater than the critical, the fracture mode is less than 100 percent shear. At the thickness where plane-strain conditions prevail, the fracture approaches 0 percent shear. This is also shown in Figure 1. Since fracture toughness is often measured in units of inch-pounds per square inch or energy per unit area, the explanation of the above behavior is not too difficult to visualize. When shear lip is being formed, the energy per unit area to create the plastically deformed volume plus the new surface increases at the same rate as the thickness. In the formation of flat fracture, the energy to form the new surface and the small plastic volumes involved remains nearly constant as the thickness increases. It is noted that the energy per unit area to form shear lip is much greater than the energy per unit area to form flat fracture.[7] For thicknesses up to t_c, the total energy to fracture, being all shear-lip-formation energy, increases faster than the specimen thickness, thus increasing fracture toughness. From t_c to the plane-strain region, the increasing area of flat fracture causes a decreasing energy per unit area, thus decreasing fracture toughness. Finally, in the plane-strain region, the shear lip is negligible, virtually all fracture is flat, and the total energy to fracture increases proportionately with the thickness, resulting in constant energy per unit area or fracture toughness. From this critical thickness concept, it is clear that a material which may have adequate fracture toughness at thickness t_1 may have very poor toughness at thickness t_2 (see Figure 1).

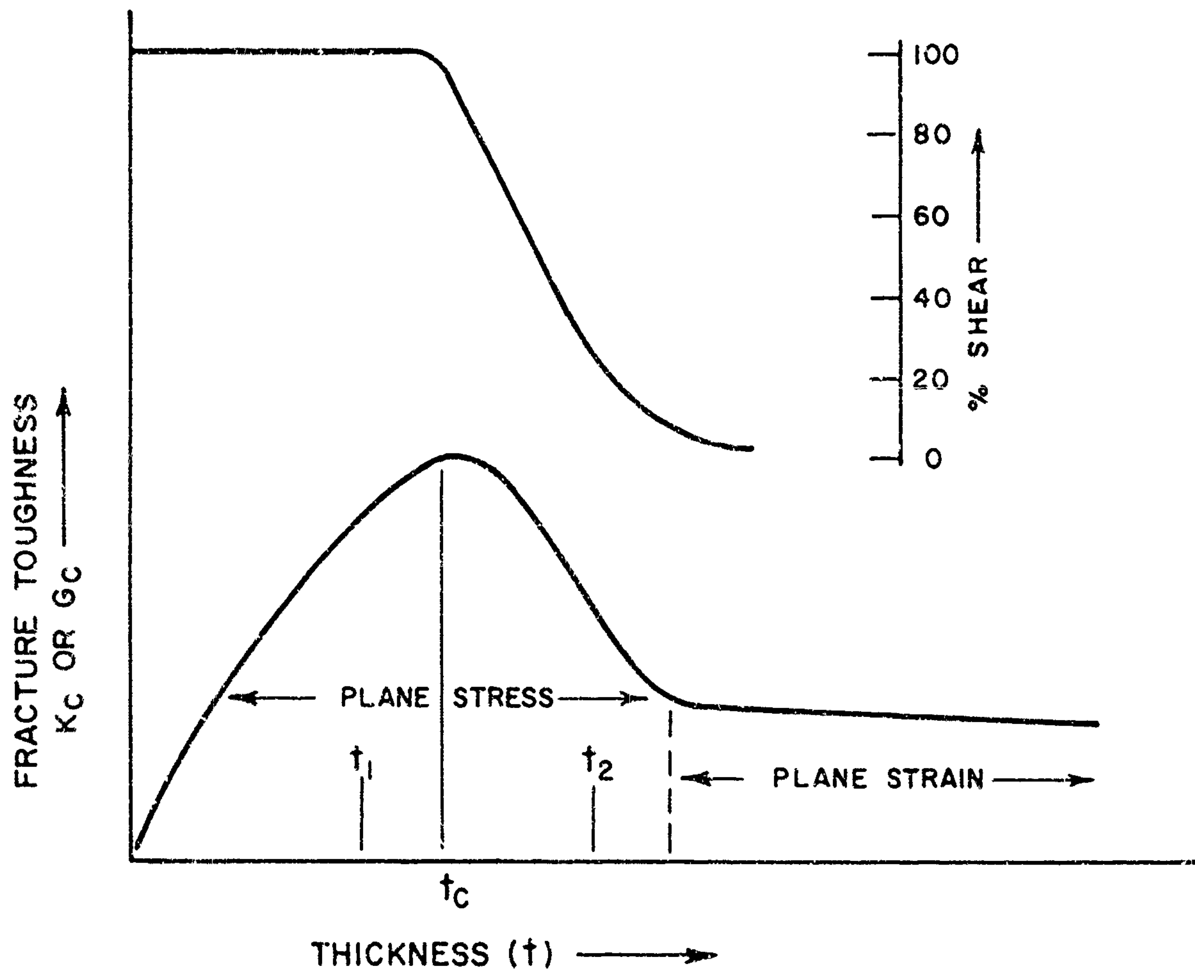

Figure 1. FRACTURE TOUGHNESS AND FRACTURE APPEARANCE VERSUS THICKNESS

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EXAMPLES OF THE USE OF THE CRITICAL THICKNESS CONCEPT IN DESIGN

Three cases will now be examined: (1) where critical thickness was not considered in design but the thickness chosen was below the critical thickness; (2) where the fracture toughness was assumed to remain adequate when the thickness was increased almost 2-1/2 times; and (3) where the critical thickness of the material was taken into account.

The 2.75-Inch-Diameter Rocket Motor Case

The 2.75-inch-diameter rocket motor case was composed of two sections separated by an internal bulkhead. The rocket motor section had a wall thickness of 0.020 inch and the booster section had a wall thickness of 0.040 inch. The case was fabricated by deep-drawing the rocket motor section with bulkhead and attaching the booster section to the bulkhead end by girth welding. H11 steel was selected because it could be heat treated to the

desired strength level utilizing air-cooling which causes less distortion than liquid quenching techniques. While the material specifications required a minimum yield strength of 190,000 psi, yield strengths of about 220,000 psi were usually obtained in practice. No fracture-toughness requirements were specified.

The U. S. Army Materials Research Agency (AMRA) was requested to evaluate the adequacy of the material for the application which required satisfactory operation at ambient temperatures down to -65 F. (No elevated temperature problems existed as a result of case insulation.) H11 sheet tensile specimen blanks were heat treated, using the same heat treatment given the motor cases, and then surface ground to a thickness of 0.020 inch to permit measurement of smooth and notch tensile properties. These specimens were then tested over a range of test temperatures down to -200 F. Concurrently, several cases were burst tested at room temperature and at -65 F under both static and dynamic loading conditions. The resulting test data is summarized in Tables I and II, and photographs of the burst vessels are shown in Figure 2.

TABLE I

Sheet Tensile Data From 0.020-Inch-Thick Sheet

Unnotched Tensile Strength* (psi)	Notched Tensile Strength** (psi)	Test Temperature (°F)	Fracture (% Shear)
249,700	200,300	Room (70)	100
251,500	200,600	32	100
263,000	203,800	-40	100
265,000	201,000	-65	100
265,000	161,600	-100	60
282,000	153,500	-200	20

*Average of two tests

**Average of three tests

Room temperature fracture toughness $(G_c) = 850 \frac{\text{in-lb}}{\text{in}^2}$

Table I shows that fractures of tensile specimens occurred by 100 percent shear at test temperatures down to -65 F, and that the notch strength remained constant at 200,000 psi at temperatures between -65 F and room temperature. The consistently high notch strengths over this temperature range are indicative of relative freedom from brittle fracture even in the presence of defects (0.001-inch radius notches). It is also noted that burst testing at -65 F yielded 100 percent shear fractures with consistently high burst pressures. The hoop stress at burst is also consistent with the unnotched tensile strength at -65 F.

TABLE II

Burst Test Data On 2.75-Inch-Diameter H11 Rocket Motor Case

Case	Test Temperature (°F)	Test Type	Burst Pressure	Fracture (% Shear)	Hoop Stress* (psi)
606	Room	Static	3625	100	250,000
261	-65	Static	3975	100	273,000
651	-65	Static	3975	100	273,000
460	-65	Static	3850	100	264,000
594	-65	Dynamic**	4025	100	280,000

Average wall thickness per case - 0.020 inch (average of 25 to 30 readings)

*Computed from $\frac{PR}{t}$

**Time from zero to burst pressure = 28 milliseconds

NOTE: Fracture of Case 651 did not originate at the visible lap.

The fracture profile in Figure 3 for the 0.020-inch-thick motor case displays the full (100 percent) shear fracture surfaces which were obtained at -65 F. In several instances, fractures which initiated in the motor case where the section thickness was 0.020 inch propagated into the booster section where the wall thickness is 0.040 inch. A photograph of such a fracture surface (-65 F) is contained in Figure 4 with fracture profiles attached showing the percent shear fracture. Notice in this figure that the fracture varies from 100 percent shear in the 0.020-inch section down to 40 percent shear in the 0.040-inch section, a clear indication that the 0.040-inch thickness exceeded the -65 F critical thickness for this material.

The 6.0-Inch-Diameter Rocket Motor Case

a. H11 Rocket Motor Case

Based on the same considerations of yield strength, air-hardenability, and environmental conditions (but again with no fracture toughness requirements specified), it was decided to fabricate a 6.0-inch-diameter rocket motor case from H11 steel. However, the wall thickness of the 6.0-inch-diameter rocket motor case was to be 0.047 inch or roughly 2.5 times as thick as the 2.75-inch-diameter rocket motor cases. The 6.0-inch-diameter rocket motor case was deep drawn and heat treated to essentially the same yield strength as that used for the 2.75-inch case. Although the design pressure (1600 psi) results in a hoop stress requirement of only about 100,000 psi because this case is heated to 1300 F during operation, it was necessary to use the H11 steel at a room-temperature yield strength of about 200,000 psi.

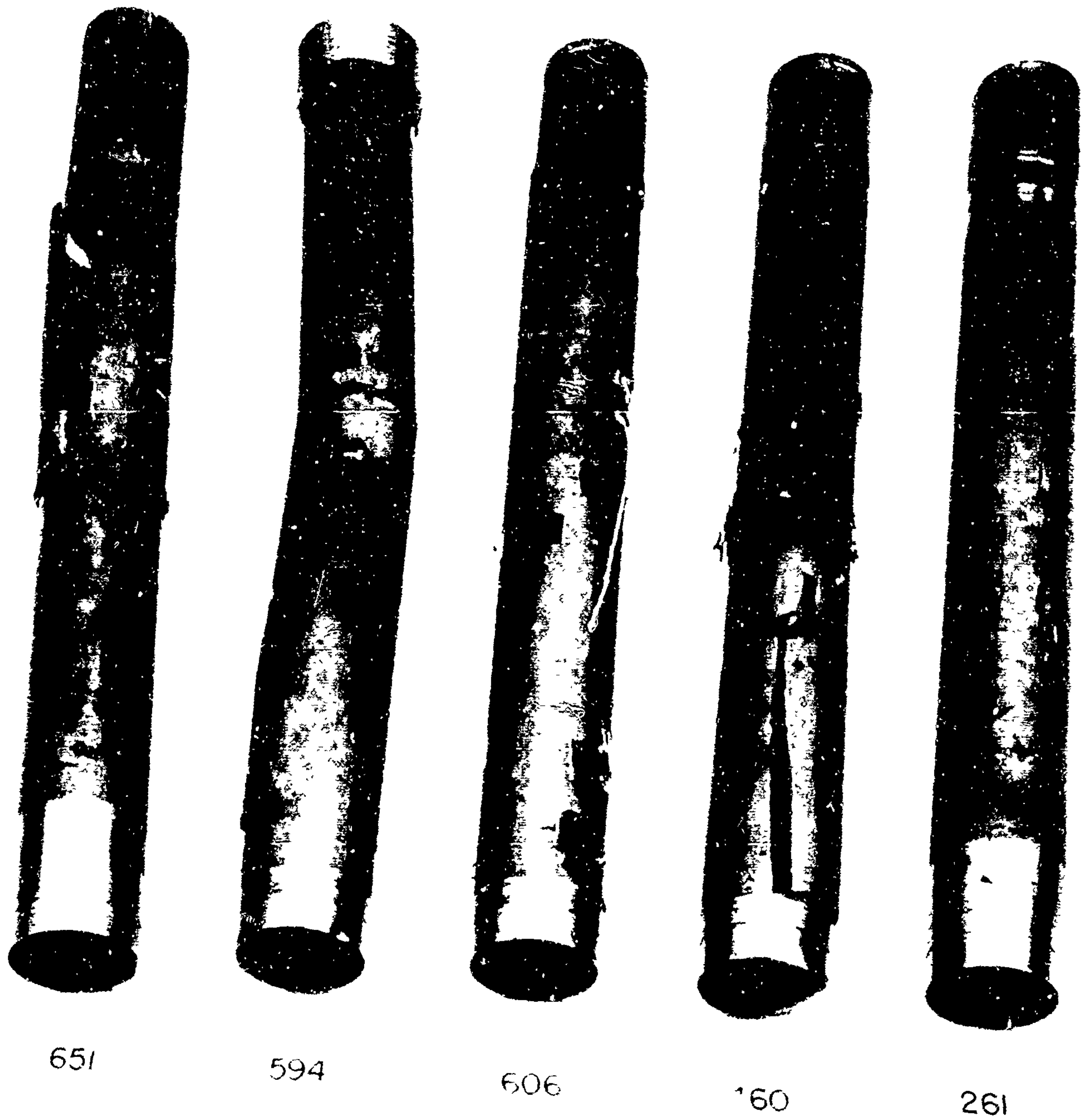

Figure 2. 2.75" DIAMETER CASES AFTER BURST TESTING AT -65F

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Figure 3. FRACTURE PROFILE OF 0.020" H11 SHEET

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From the behavior illustrated in Figure 4, a brittle failure problem, at low temperatures, in using H11 steel in sections thicker than 0.020 inch should have been anticipated; however, critical thickness was not a design criterion. Tests conducted at AMRA on these H11 steel 6.0-inch-diameter rocket motor cases indicated that, although the material possessed adequate strength, the fractures at -65 F tended toward brittle failure. Subsequent tests conducted by various investigators.[5,6,14] independent of the above program, determined the critical thickness of H11 steel at the strength level used in the 6.0-inch-diameter rocket motor case to be approximately 0.040 inch at room temperature and much less than this value at -65 F. The H11 6.0-inch-diameter rocket motor case was therefore designed to have a section thickness which exceeded the critical thickness, and this resulted in the brittle behavior observed at -65 F. Figure 5 shows the fracture surface of one of the 6.0-inch-diameter rocket motor cases which failed in a brittle manner. Had data on the critical thickness been utilized at the design stage, this costly error could have been eliminated.

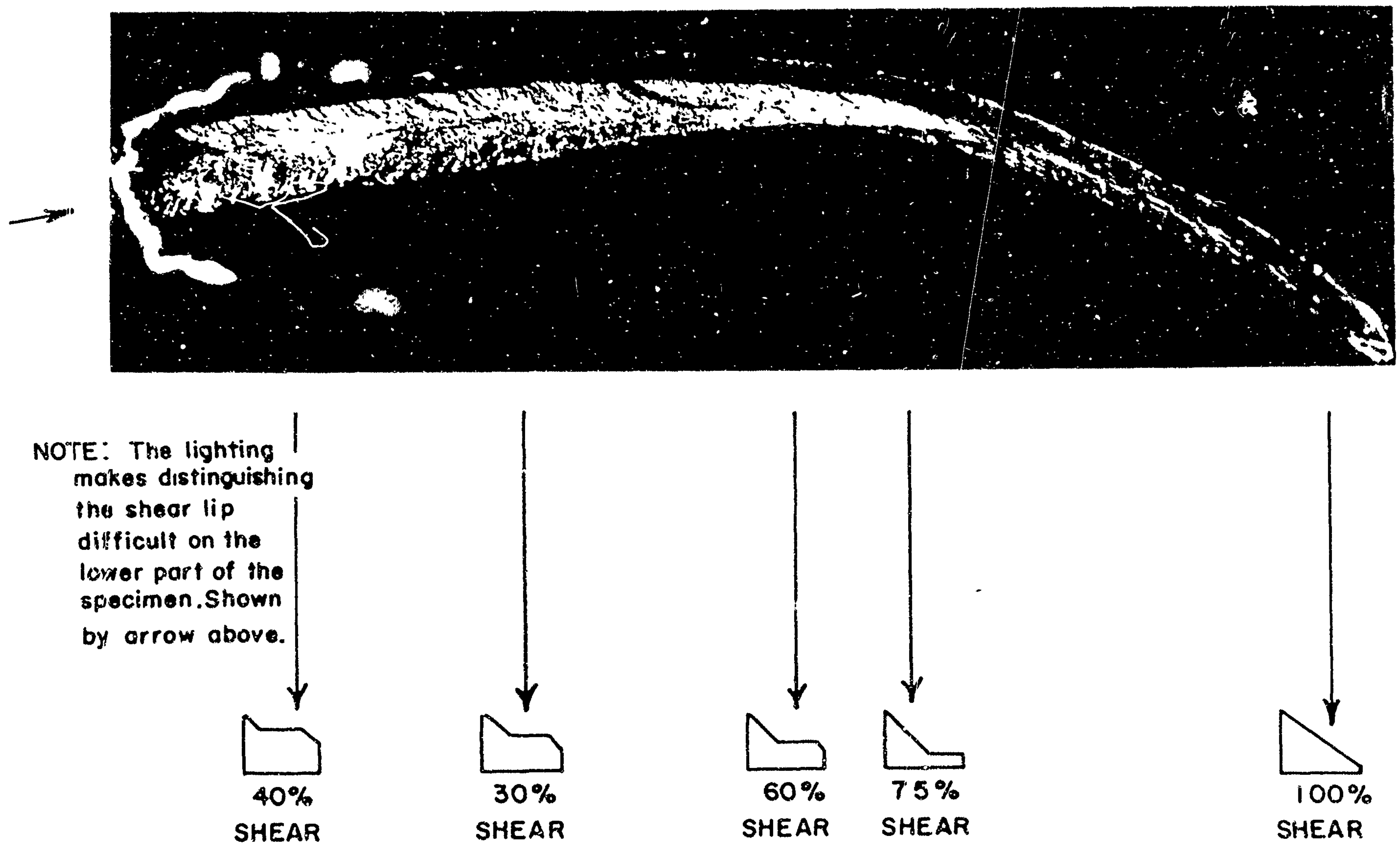

Figure 4. FRACTURE SURFACE OF A BURST FRAGMENT OF AN H11 ROCKET MOTOR SHOWING DECREASING SHEAR LIP AS FRACTURE PROPAGATES FROM A SECTION THICKNESS OF 0.020 TO 0.040 INCH 10X

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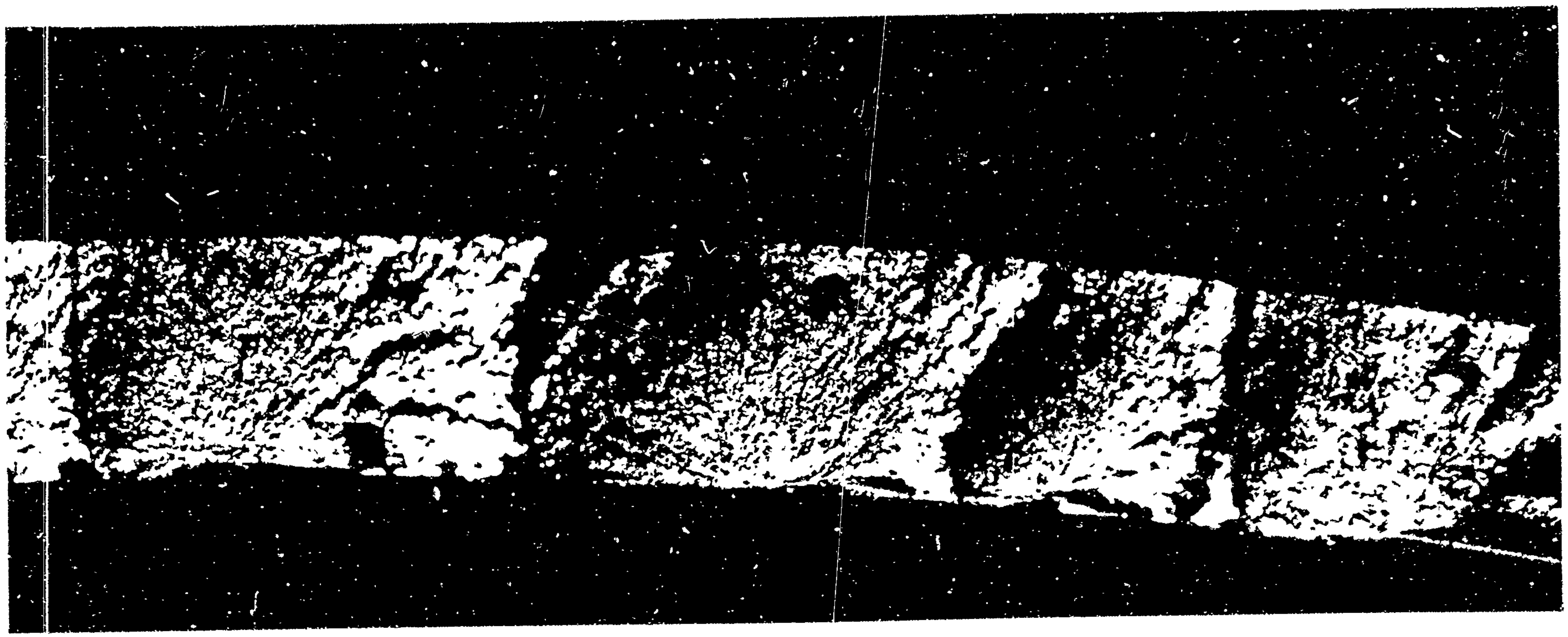

Figure 5. FRACTURE ORIGIN IN 6.0" DIAMETER H11 CASE

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b. D6AC Rocket Motor Case

As a result of the brittle behavior of the H11 6.0-inch-diameter motor cases, AMRA recommended that the material be changed to D6AC steel. This steel would provide approximately the same mechanical properties as H11 steel and, although critical thickness data was not available, per se, it was known from the work of Sliney[15] that D6AC steel in the condition recommended exhibited full shear fracture to temperatures below -65 F and therefore was at or below its critical thickness. Based on this reasoning, it was anticipated that the use of D6AC steel would eliminate the problem of brittle failure of 6.0-inch-diameter motor cases at low temperatures.

Subsequently, AMRA was provided with several D6AC steel 6.0-inch-diameter motor cases for burst tests and fracture toughness measurements. Burst tests were carried out at temperatures ranging from room temperature down to -85 F.[16] These tests resulted in no premature or brittle failures. One motor case was fatigue-cracked to contain a through-the-thickness fatigue crack over one-half inch long. The burst pressure of this motor case still exceeded the design stress by an appreciable margin. Fracture toughness measurements on 6.0-inch-diameter motor cases having eloxed through-the-thickness notches were carried out at room temperature and -65 F. These tests resulted in 100 percent shear fractures with adequate fracture toughness. The data obtained from this program is presented in Table III which shows that all fractures occurred by a 100 percent shear mode even at temperatures down to -85 F. A photograph of one of these cases and its fracture appearance is presented in Figure 6.

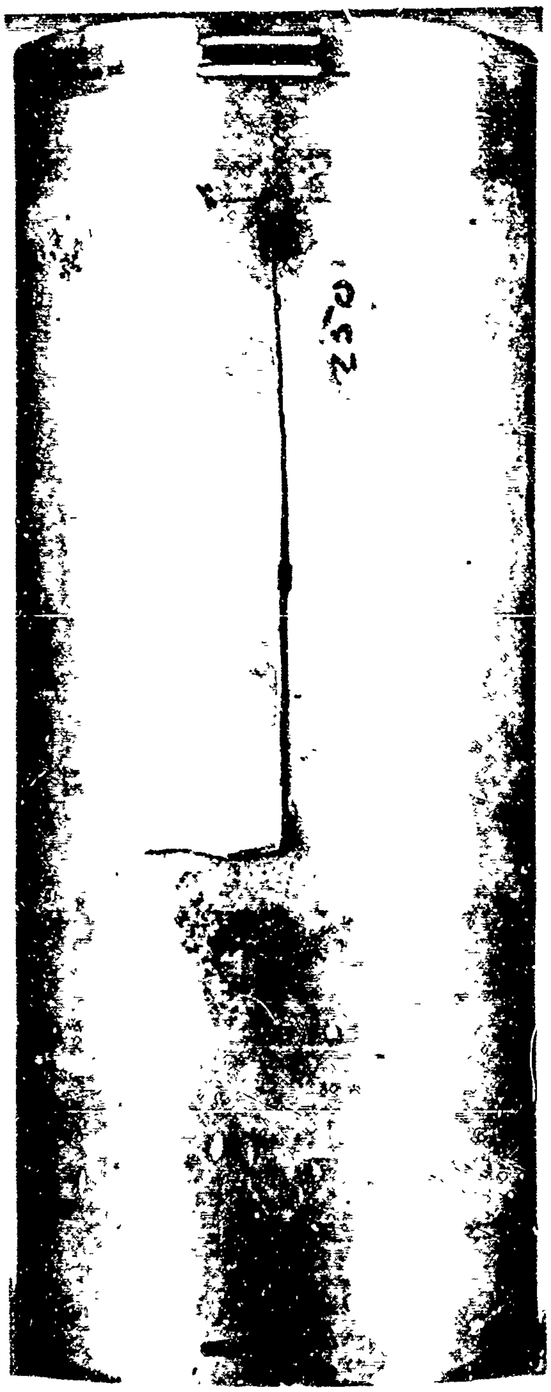
TABLE III

Burst Test Data For D6AC 6-Inch Diameter Motor Cases

Case	Pre-existent Crack Length (inches)	1/2 Slow Crack Length A_{cr} (inches)	Burst Pressure (ksi)	Stress σ (ksi)	K_c (ksi)	Shear (%)	Test Temp (°F)
112	None	-	3.8*	-	-	-	-65
114	None	-	3.7	244	-	100	70
106	None	-	4.0	253	-	100	-55
116	None	-	4.0	254	-	100	-65
111	None	-	3.9	249	-	100	-85
104	None	-	3.9*	-	-	-	-200
115	0.150	0.148	3.1	196	172	100	70
101	0.250	0.300	2.9	183	156	100	-65
110	0.150 fatigued to 0.55	0.257	1.6	102	144**	100	70
105	0.150 fatigued to 0.610	0.305	1.4	88.6	90**	100	70
113	0.150 fatigued to 0.30	0.173	2.4	151	168	100	70

*Yielded without fracture, end closure leak.

**Case failed during cycling, K_c value low due to strain hardening (yielding) during fatigue cracking.



TOP: DUCTILE FAILURE OF D6AC 6.0"-DIAMETER ROCKET MOTOR CASE. NOTE THE FULL SHEAR LIP ALONG THE ENTIRE LENGTH OF THE FRACTURE. TESTED -65 F.

RIGHT: SLOW CRACK GROWTH EMANATING FROM A THROUGH-THE-THICKNESS SLOT (10X)

Figure 6. 6.0" DIAMETER D6AC MOTOR CASE 101

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It is clear from these case histories that a material, processing method, and heat treatment which are adequate for one solid propellant missile application are not necessarily adequate for another. In the examples cited, a thickness increase of 0.027 inch was sufficient to render the H11 steel too brittle for low-temperature service use. It is also clear that the "critical thickness" concept can be applied to steel sheet to obtain very easily a qualitative assessment of the adequacy of the steel with respect to low-temperature brittle fracture.

SUMMARY AND RECOMMENDATIONS

The three rocket motor cases discussed above were all properly designed with regard to yield strength, operating stress field, operating environment, geometry, etc. However, the low-temperature brittle behavior of one case was due to a thickness-controlled loss of fracture toughness at low temperature. While the authors realize that a comprehensive testing program to gather data on the effect of thickness on the fracture toughness on every alloy under consideration for a given application would be exceedingly expensive in terms of both time and money, they do advocate that the critical thickness concept be used in a qualitative manner before finalizing the design. For example, if several notched tensile specimens in the same conditions of heat treatment, chemistry, surface finish, etc., as the end product are tested at the lowest anticipated service temperature, the resulting fracture appearance and notch toughness may give a qualitative idea of its resistance to brittle failure.

A simple method is available to obtain an estimate of the critical thickness. This method also allows a determination of critical thickness variation with test temperatures. If a series of specimens which are significantly (about 50 percent) thicker than the intended design thickness, and which have been given the same heat treatment as the end product, are tested at various temperatures, the critical thickness as a function of test temperature can be determined from shear lip measurements. The total shear lip width (sum of shear lip on each side) is equal to the critical thickness at the particular temperature used. This relationship is illustrated schematically in Figure 7. However, it must be remembered that changing the thickness also changes the percent reduction and may thus change the fracture toughness. For this reason, it is imperative to test several specimens at the thickness to be used in the end product. It must also be remembered that the relation of shear lip and fracture toughness holds only for low- and medium-alloy steels and has not been observed in titanium alloys.

The above examples illustrate a situation where a small change in thickness (0.027 inch) severely affected resistance to brittle failure of a component. However, thickness is not the only materials parameter which can be of critical importance in structural applications. Small changes in composition (interstitial elements), heat-treatment cycle, or use environment can also critically affect resistance to crack propagation. When

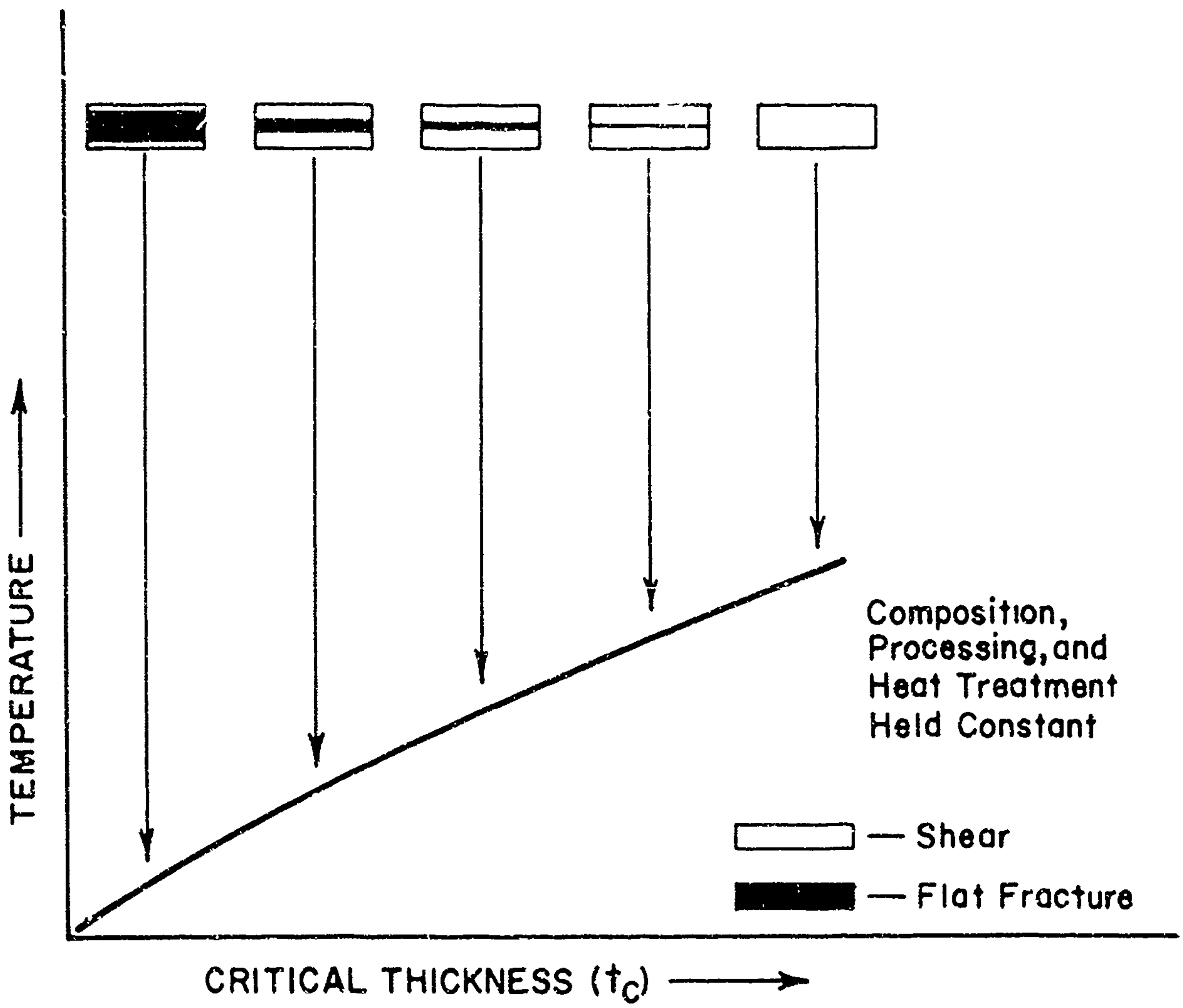

Figure 7. CRITICAL THICKNESS VERSUS TEST TEMPERATURE 19-066-398/AMC-64

making any changes in any materials parameter, the designer should secure actual test data to substantiate that the material will possess adequate fra ture toughness under the most severe operating conditions required of the component.

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II. Abbott, Kenneth H.
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